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RESEARCH MEMORANDUM

THE EFFECTS OF POWERED CONTROLS AND FIRE-CONTROL

SYSTEMS ON TRACKING ACCURACY

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and Burnett L. Gadeberg

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SUMMARY

This report continues an analysis of the relationship between air-
plane and systems characteristics and tracking accuracy being conducted
at the Ames Aeronautical Laboratory by considering the effects of insert-
ing powered flight controls and complex fire-control systems into the
pilot-airplane tracking loop. A brief summary of the principal results
of the program completed thus far is included.

With regard to powered control systems, it was indicated that various
stick-force-feel devices and the static gearing of the control system
were not critical in themselves. The only system tested which the pilots
could not cope with had a large breakout force which made the stick-force
and stick-position response either indeterminate or very small at the
actual values of stick force and control-surface position the pilot used
in tracking. When the breakout force was reduced the tracking errors
were reduced to a satisfactory level.

With regard to fire-control systems, both an optical disturbed-
reticle sight and a scope-presentation director system with automatic
radar tracking were evaluated. The most significant effect noted was
a threefold increase in the gun-line wander when the disturbed-reticle
sight was operated with large values of gain of the lead-angle computer.
This increase is shown to be associated with the dynamic response of the
lead-angle computer.

INTRODUCTION

This report continues the discussion of the airplane and systems
characteristics which critically affect tracking accuracy that was
initiated in references 1 and 2. The previous papers dealt primarily
with the aerodynamic behavior of the airplane; the present paper considers

the effects of inserting two additional dynamic elements - powered flight controls and fire-control systems.

The same experimental procedure has again been used, that is, to isolate critical characteristics by comparing the tracking performances with a wide variety of complete systems in the single standard test maneuver shown in figure 1. The man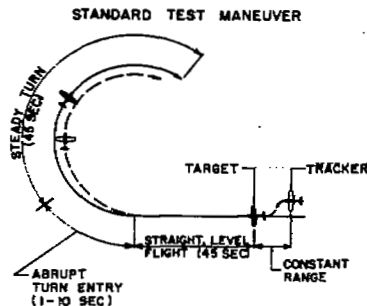euver consists of three segments, a steady straight tail chase, an abrupt breakaway turn entry where the target is maneuvering as fast as it can, and a subsequent steady turn at constant normal acceleration. The comparisons to be made herein involve only the two constant g segments. The numerical basis for comparing the tracking will be the standard deviation of the oscillations about the mean aiming point. This will be termed the aim wander. An aim wander of 2 mils implies that the pilot was able to keep the aiming point within 2 mils of its average position approximately 70 percent of the time during the run.

Figure 1

DISCUSSION

Powered Flight Controls

The effects of control-feel characteristics typical of current powered control systems were scrutinized by comparing a large number of contemporary fighters with the World War II F-51H and F8F airplanes with manual control. 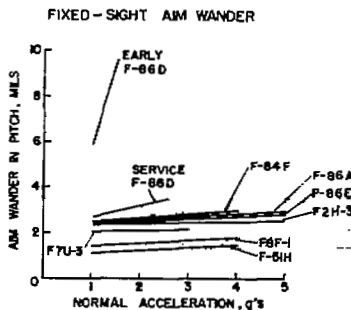Figure 2 is a comparison of the fixed-sight aim wanders in pitch plotted as a function of the normal acceleration. The various longitudinal control systems represented include the F-86A (power-boosted elevators with force-feedback plus bob-weight), the F2H-3 and F-84F (irreversible elevators and artificial feel), the F7U-3 (irreversible ailevators), the F-86E (irreversible linked stabilizer and elevator), an early version of the F-86D (irreversible one-piece all-movable tail), and the same F-86D with the present standard service control system. All of the aim wanders are the same order as those of the F-51H and F8F with manual controls (control-surface hinge moments reduced by aerodynamic balance) except the values for the early model F-86D which are as much as four times as large.

Figure 2

First, consider the group of systems which have reasonably low aim wanders. They include quite a wide variety of artificial-feel devices,

such as springs, bobweights, gain changers, q-boxes, and dampers, and include all of the mechanical elements found in the unsatisfactory system; therefore the control-feel devices do not appear to be the critical factor in the tracking problem. Further, the static gearing of the control system in itself does not appear to be critical since the satisfactory systems also encompass the values of stick force per g and stick movement per g encountered on the unsatisfactory system. This underscores a recently published tracking study by Abramovitz and Van Dyke, reference 3, in which these parameters were isolated on a variable-gearing manual-control system with similar results; the pilot was able to track even with control-system gearings which were unsuitable for normal flying.

The remaining consideration is the dynamic response of the control system. Some earlier work by Phillips, Brown, and Matthews (ref. 4) suggested that the dynamic response, specifically the phase angle between the applied stick force and the control-surface response, would be critical, at least in abrupt maneuvers with large control deflections. Therefore the frequency response of several of these systems was measured for control-surface deflections of 0.4° for the airplanes with elevators and 0.2° for the airplanes with all-movable tails. Figure 3 shows the amplitude ratio and phase angle between the stick force and the control-surface position as a function of frequency. The early F-86D system, and the modified system as well, are distinguished from the others by very large phase lags. Since the large phase lags were not reduced in the satisfactory system, they do not appear to have hindered the tracking.
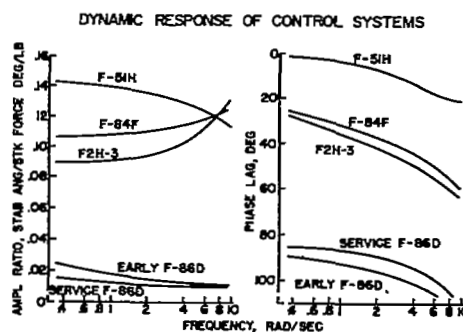

Figure 3

It is apparent that the initial examination of the dynamic response was not adequate. An examination of time histories of the stick-force and control movements during the tracking runs indicates that tracking is essentially a task involving making small corrections to a smooth average fligh path; therefore it involves small control displacements and small stick forces at very low operating frequencies. The difficulty with an analysis such as that in figure 3 is that the response of the control system at the small movements actually involved in tracking is very nonlinear. Figure 4 is a comparison between the responses of the satisfactory and unsatisfactory systems in the same airframe for the ranges of stabilizer position and operating frequencies the pilot actually used in tracking. The increment in the stabilizer position output is shown as a function of the
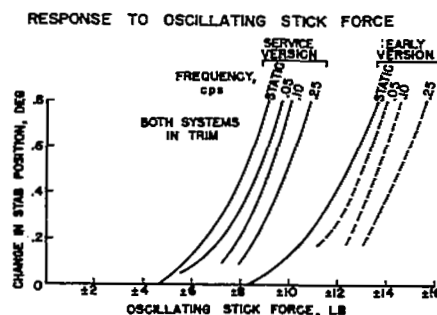

Figure 4

oscillating stick-force input for three frequencies: 0.05, 0.10, and 0.25 cycles per second, with the systems in the trimmed position. The response also varies nonlinearly with the setting of the trimming device. The curves are shown to the lowest values of stabilizer angle and frequency at which a steady response could be measured. The response for the original system is shown dotted for frequencies other than zero because the data had to be obtained on another system of the same type and corrected to the static gearings used in the tracking tests.

The chief difference between these two systems is the sizable reduction in the stick force at which the stabilizer begins to respond. This corresponds to a reduction in the static breakout force from 8 pounds on the unsatisfactory system to 4-1/2 pounds on the satisfactory system. The deadband or region of stick forces wherein there is either no response or a small inconsistent response of the stabilizer has been cut in half, and it is precisely this band within which the pilot desires to operate the system in order to track well. The response to stick force has been shown because the pilot is generally assumed to fly by force feel if he can. The responses to stick position have also been examined and look very much like those shown for the stick force. A deadband in the stick position due to backlash and slop has also been cut in half, from about 0.2° to 0.1°. In essence then the pilot could not track well because at the small stabilizer movements needed to do good tracking, this particular control system had little or no definite response to either stick force or stick position.

Now it would be interesting to compare, say, the specific phase lags and time constants for these two systems to see what values the pilot could cope with. Unfortunately, the actual tracking motions are nearly all within the region where such dynamic response measurements are either unreliable or indeterminate. For this reason, rather than attempting too profound an analysis on the basis of this one unsatisfactory system, we have begun an additional test program wherein an F-86D will be modified to incorporate a variable-response control system in which each of the significant response parameters can be isolated in turn.

Fire-Control Systems

Next the influence of the dynamic response of the fire-control system will be considered. Several systems typical of the different types now in service have each been evaluated when computing a lead-pursuit course, but with the target performing the same standard test maneuver so that the data are directly comparable with the previous fixed-sight results.

When a fire-control computer is inserted in the pilot-control-system-airplane tracking combination, some new geometry must be considered. Figure 5 illustrates some significant terms. The line of sight L is the true line in space from the tracking airplane to the target. It is measured from a reference axis fixed in space. The gun line or armament reference line is the longitudinal axis of the tracking airplane. It must lead the line of sight by a certain angle in order to score a hit. This required position of the gun line is indicated to the pilot by means of the tracking line which is an apparent line in space the pilot sees when he looks

Figure 5

through the gunsight reticle. The reticle is mechanically offset from the gun line by the computed lead angle P furnished by the fire-control system, thus when the pilot maneuvers the airplane so that the reticle is exactly on the target the gun line has the desired lead angle with respect to the line of sight. A small error in tracking has been shown for clarity. With a fixed sight the tracking line is rigidly attached to the gun line at an arbitrary angle and their motions are identical. With a computing sight their relative motions depend on the dynamic response of the computer and will be an important concern in the rest of the report.
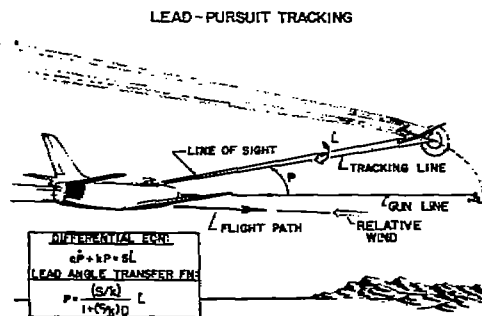
The gun-line motions are pertinent to projectiles which are not significantly affected by the relative wind, such as cannon shells or spin-stabilized rockets. For projectiles which "jump" or aline themselves with the relative wind, such as conventional rockets with fins, the flight path must be considered rather than the gun line. The flight path differs from the gun line by an amount depending on the angle of attack and the pitching velocity.

Figure 5 has illustrated a system where the tracking information and the target are directly visible to the pilot. There are other systems where the target is not visible and the desired gun-line position is represented on the face of an oscilloscope. These will be discussed as the test results are presented.

Since it is desired to compare the effects of changing the dynamic response for several types of fire-control system, the first problem is to select some common numerical basis to describe the responses of widely different systems. Not only are the individual inputs and outputs physically different, but there are both electrical and mechanical analog computers with completely different physical constants. Something fundamental is required, and for this purpose the differential equation involving the lead angle, the basic building block in all of the computers, will be examined as indicated in figure 5. The resulting open-loop lead-angle transfer function relating the lead angle P to the angular

velocity of the line of sight $\overset{\bullet}{L}$ contains a gain and a first-order time
constant which are to be found in some form in any system.

The term, gain, which will be the primary test variable, is the
required constant of proportionality between the basic computer input,
the angular velocity of the line of sight, and the computer output, the
lead angle. The numerical value of the gain depends on ballistics, such
as the velocity of the projectile, and on the flight conditions, such as
the range. In this case, the test maneuver holds enough quantities con-
stant so that the gain can be expressed physically by the projectile
flight time in seconds. The time constant is a lag term which is intro-
duced by the necessary filtering in an electrical analog or damping in
a mechanical analog computer. The numerical value is usually a simple
constant in an electrical analog; in a mechanical analog it is the ratio
of the damping coefficient to the gain as shown in the equation in
figure 5.

The individual systems tested as implied vary in a number of details.
For simplicity only two will be described: the actual computer inputs
used to represent the line-of-sight rate, and the actual outputs used to
indicate the desired lead angle to the pilot. The block diagrams and
transfer functions of the individual systems are presented in figure 6
for reference; however, the tracking per-
formances will be plotted as functions of
the gain and time constant so that direct
comparisons between systems can be made.

INDIVIDUAL SYSTEM DIAGRAMS
AND TRANSFER FUNCTIONS
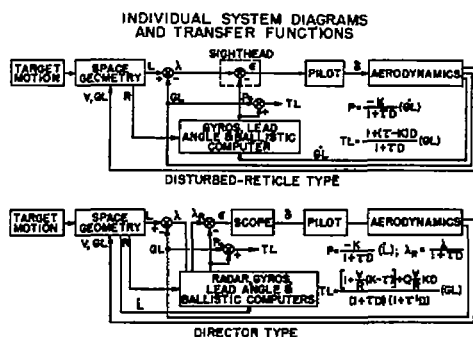
DISTURBED-RETICLE TYPE

DIRECTOR TYPE

Figure 6

Disturbed-reticle system.- The first
system considered, the A-1 sight in the
F-86A airplane, is classified as a disturbed-
reticle system. The actual input to the
computer is the angular velocity of the gun
line, rather than that of the line of sight,
which is called for in the lead-angle equa-
tion. This substitution is made to elimi-
nate the need to provide equipment to
measure the true line of sight. The result of this substitution is the
distinctive feature of this system as far as tracking is concerned - a
change in the computed lead angle must be generated by a motion of the
tracking airplane, that is, by the pilot disturbing the gun line. The
actual output of the system is the position of the tracking line which
is presented to the pilot on the windshield for direct visual comparison
with the real line of sight, the particular system illustrated in
figure 5.

Figure 7 shows the effect of changing the gain of the lead-angle computer (expressed as projectile flight time) upon the three significant wanders: tracking line, gun line, and flight path. The shaded regions are the envelopes of all of the test points. The lowest value of gain corresponds to a short range, 800 feet, and high altitude, 35,000 feet; the highest corresponds to a long range, 3,000 feet, and low altitude, 10,000 feet. At each test value of gain the time constant was varied within the limits shown by changing the damping in the computer mechanism. The average fixed-sight aim wander in the same airplane is shown for comparison.
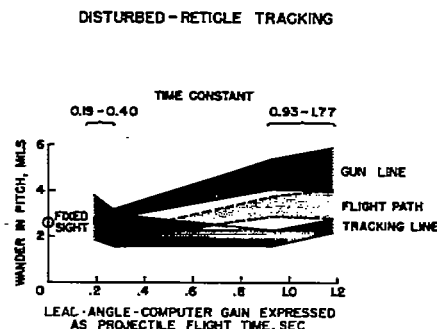

DISTURBED-RETICLE TRACKING

Figure 7

The tracking-line wanders are not significantly affected by any of the changes in the system response. It is apparent that the pilot was able to cope with all of these changes and track as accurately as he could with a fixed sight. This also implies that fixed-sight aim wanders are a good indication of the tracking wanders to be expected when a disturbed-reticle system is added to the tracking loop.

The gun-line wanders, however, which are a measure of the dispersion imposed on small jump-angle projectiles, increase proportionally with gain to about three times the tracking-line wanders, or to the order of 6 mils. This increase is readily explained. It is associated with the changes in the frequency response of the lead-angle computer which are illustrated in figure 8. The amplitude ratio, or ratio of gun-line input to tracking-line output, is shown as a function of frequency at the lowest and the highest values of gain tested. At the low gain, short range, where the lead required is small, the ratio of gun line to tracking line is nearly 1 at normal operating frequencies - the two are closely coupled and, in effect, approach a fixed sight. At high gain, long range, or long flight times, where the lead required is large, the amplitude ratio increases significantly at operating frequencies, and a larger motion of the gun line is required to generate the required lead angle. Thus, the increase in the gun-line wanders observed in the flight tests is inherent in the lead computation and is associated with the principle of using the gun line as the input to generate the lead angle.

FREQUENCY RESPONSE OF DISTURBED-RETICLE SIGHT
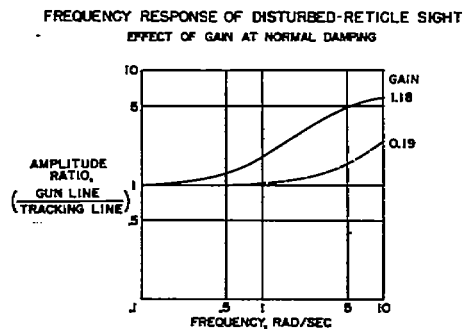EFFECT OF GAIN AT NORMAL DAMPING

Figure 8

The flight-path wanders, of course, show the same tendency to increase as the gun-line wanders; however, the numerical values are

smaller, of the order of 3 mils, and do not appear to be significant
since they apply only to projectiles with large jump angles, such as
conventional rockets, which inherently have comparatively large disper-
sion angles.

The effects of changing the system damping coefficient, which is
the ratio of the time constant to the gain, are worthy of separate note.
The test points corresponding to the different time constants showed the
same two trends at each value of gain. There were no significant varia-
tions with time constant, but there was a large random scatter of the
amount indicated by the envelope on figure 7. Both of these observa-
tions have been explained by studying the changes in the pilot's behavior
corresponding to the changes in the system damping, particularly the
frequency content of his tracking motions.
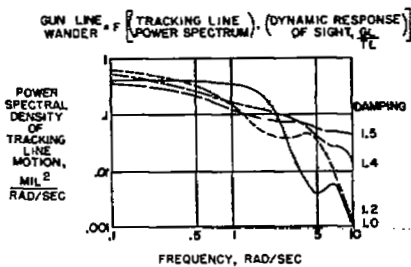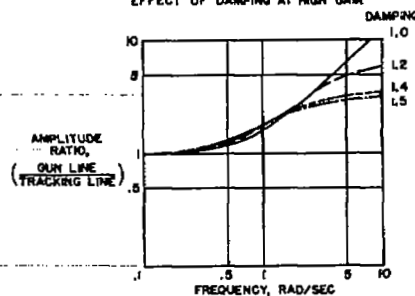

Figure 9   Figure 10

Figure 9 shows the relative amount of the tracking-line motion as
a function of the frequency of the motion at four different values of
damping. When the system is well damped, the pilot still makes rapid
high-frequency corrective motions. When the system is poorly damped,
the pilot moves the system primarily at low frequencies, that is, slowly
and smoothly. By referring to the frequency response of the sight at
the same four values of damping, figure 10, it can be seen that, in
effect, the pilot is confining the frequencies at which he operates the
system to those frequencies below the frequency (about 4 radians per
second) at which the system response begins to change significantly with
damping. Thus, this compensation by the pilot is the reason that there
was no consistent variation of gun-line wander with damping or the time
constant. The second observation, the amount of scatter, is due to the
fact that the pilot, being human, is inconsistent. The test results
indicate considerable random variation in the pilot behavior from the
average values shown in figure 9, even under identical test conditions.

The reason the pilot behavior has been stressed is that it must be
considered when attempting to predict the gun-line wander with a new
fire-control system or a different airplane. As indicated by the general
relationship at the top of figure 9, the gun-line wander can be predicted

by applying the known transfer functions of the new system to existing
tracking-line or fixed-sight aim-wander data. However, it has been found
that a variation of the tracking-line power spectrum with damping must
be included. In order to get some idea of how general the empirical
averaged variations shown in figure 9 might be, these data have been used
to predict the gun-line behavior of the Navy Mark 16 sight in the FJ-2
airplane with good accuracy; however, the variations in the sight mechan-
ics and certainly the airframe in this case may not be large enough to
be a significant test. A more complete discussion of these disturbed-
reticle-system tracking tests has been published in reference 5.

Director system.- The next type of system considered, a modified
E-4 in the early F-86D, is classified as a director system. The actual
input to the computer is the angular velocity of the line of sight as
measured by an automatic tracking radar. The distinctive feature of
this system, therefore, is that a motion of the tracking airplane or
gun line is not required to generate the lead angle. There is a compli-
cation, however, in the fact that the line-of-sight measurement is noisy.
The actual output varies considerably from the tracking-line concept in
the previous system. Since this system must operate where the target is
not visible, the tracking output is presented to the pilot as a displace-
ment between two dots on an oscilloscope. This displacement is an arbi-
trary function of the error in the gun-line position, which the pilot is
supposed to reduce to zero.

In comparing this system with the previous one, therefore, both the
principle of the lead computer and the presentation to the pilot have
been changed. The effects of the computer response will be considered
first.

Figure 11 again shows the variation of the
gun-line and flight-path wanders with gain at
the normal computer time constant. Note that
the range of gain covered is considerably
larger than for the disturbed-reticle sight,
10 seconds compared to 1.2, to account for
long-range rockets or very low-speed projec-
tiles such as bombs. There are two signifi-
cant observations with regard to the gun-line
behavior, which was the chief item of interest
in the disturbed-reticle system. First, the
gun-line wanders with this system in the tracking loop are no larger than
the fixed-sight aim wanders in the same airplane. (Remember that this
evaluation was made in the early unmodified F-86D with the poor control
response.) Second, in contrast to the disturbed-reticle system, they are
not affected by the gain or lead angle. This would be expected since the
gun-line motions simply are not involved in the lead computation unless
there is an unwanted coupling between the motions of the airplane and the
tracking radar antenna. The corresponding flight-path wanders are of the
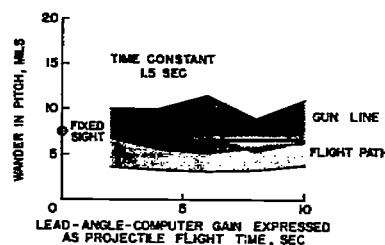
DIRECTOR TRACKING

Figure 11

order of 5 mils, again probably insignificant in comparison with the dispersion of likely projectiles.

Due to the many independent variables which affect the oscilloscope presentation of the tracking error to the pilot, no data analogous to the tracking-line wanders are shown on figure 11, although it can be deduced from the gun-line wanders that the pilot was able to track satisfactorily with this particular presentation. The more important of these variables, which require separate evaluation, include the amount of information presented as compared with a visual tracking situation, the noise in the error signal or the amount of filtering applied to it, and the scope sensitivity, that is, the particular ratio between the dot motion and the gun-line error.

Tests have been conducted at the Langley Aeronautical Laboratory to isolate the effects of the lack of target information, that is, angle of bank or attitude, in the various segments of the test maneuver. A noise-free scope presentation was simulated by tracking a very bright light in a target airplane at night. The aim wanders presented in the following table show that tracking in the steady-g portions of the test maneuver which have been considered in this report was not affected by this factor.

Target attitude information	Portion of test maneuver	Aim wander in mils	
		Pitch	Yaw
Complete, visual	Steady 1 g flight	1.2	2.1
	Steady turns	2.4	4.0
Simulated scope presentation	Steady 1 g flight	2.1	2.7
	Steady turns	3.2	5.9

The effects of noise in the tracking-error signal have also been isolated at Langley. An APQ-35 radar in an F3D airplane was used with the lead computer and filtering disconnected so that the pilot when looking at the scope simply saw the position of his own gun line with respect to a noisy representation of the target position.

Figure 12 shows the wander of the gun line as a function of the noise apparent to the pilot as represented by the root-mean-square difference between the true target position and the position indicated on the scope. The noise-free point again was obtained by the technique of visually tracking a very bright light in the tail of the target airplane at night. This point, as would be expected, coincides with fixed-sight aim wanders on the same airplane. Starting from the noise-free point, there is a very significant increase in the gun-line wander as the noise in the presentation apparent to the pilot increases.

EFFECTS OF RADAR NOISE

APQ-35 RADAR
F3D AIRPLANE
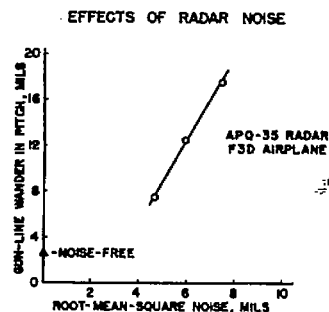
NOISE-FREE

ROOT-MEAN-SQUARE NOISE, MILS

Figure 12

In the E-4 system tests discussed previously, sufficient filtering was applied to reduce the noise level in the tests to roughly 4 mils rms, therefore this factor should not affect the previous results.

A test program to study the effects of the sensitivity of the tracking-error signal, the other important variable in the scope presentation, is just getting under way and no results are available as yet. Since the gun-line wanders are already equal to the fixed-sight wanders, no significant improvement is expected, but the critical range of acceptable sensitivity should be defined.

Before leaving the subject of director systems, reference should be made to tracking data of an optical director system. Particularly in air-to-ground use, the presence of clutter and noise often makes the use of radar tracking impractical, as figure 12 suggested. In such cases it may be desirable to consider a director system with the pilot operating an optical tracking device to furnish the line-of-sight rate input. In reference 6 Turner, Triplett, and White have shown that very low tracking-line wanders of the order of 1 mil or less can be achieved with such a system even in the presence of the motions of the tracking airplane.

CONCLUSIONS

Figure 13 summarizes some of the results of the NACA tracking research. The left-hand side of the figure shows the four major dynamic elements that comprise a tracking system: the pilot, the aerodynamics, the control system, and the fire-control system. The center section lists the more important changes in these elements which have been evaluated. The right-hand side shows the relative increases in aim wander as these changes are introduced. The shaded bar, the initial data in each case, represents an experienced pilot in a normal F-51H with manual controls and a fixed sight.
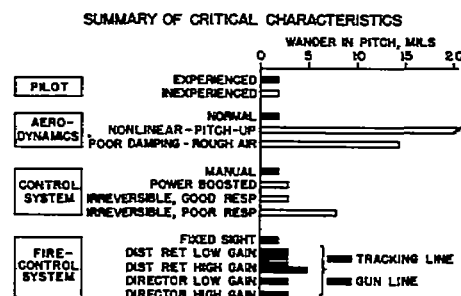
Figure 13

There were no significant variations due to the experience of the pilot (see ref. 1). With regard to the aerodynamics, introducing nonlinearities such as pitch-up resulted in the airplane becoming uncontrollable in the tracking sense (see ref. 1). Introducing poor lateral-directional damping in the presence of moderately rough air resulted in aim wanders of the order of 15 mils (see ref. 2). With regard to the control system, introducing power-boosted or irreversible controls with good dynamic response had small effect, but irreversible controls with poor response increased the aim wanders to the order of 8 mils. And, finally, with regard to the

fire-control system, the most significant critical effect noted was a
twofold to threefold increase in the gun-line wanders of a disturbed-
reticle system at high values of gain and time constant.

Ames Aeronautical Laboratory
    National Advisory Committee for Aeronautics
        Moffett Field, Calif., Apr. 12, 1955

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